SEA-SURFACE TEMPERATURES IN THE WAKE OF HURRICANE BETSY (1965)

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ABSTRACT

Following the passage of hurricane Betsy (1965) through the Gulf of Mexico two flights were made five days apart aboard a research aircraft to collect sea-surface temperatures with an infrared radiometer. The purpose was to study the effects of a hurricane on the sea-surface temperatures field. Data from the first flight, which occurred one to two days after the hurricane passage, showed two cores of colder water to the right of the storm's track and very little structure to the left. The flight made five days later still showed a core of colder water to the right, but by this time its shape had been badly distorted by the surface current system. These results are compared with the findings of other investigators, and the value of real-time synoptic coverage with the use of aircraft is pointed out. The plan for an experiment utilizing aircraft and airborne oceanographic techniques to provide a 3-dimensional picture of the ocean temperature structure prior to and following a hurricane is also presented.

1. INTRODUCTION

There has been considerable interest shown in recent years in the effects of the passage of a hurricane on sea-surface temperature. While it is agreed that the hurricane causes a cooling of the sea surface of up to 5° C., there appears to be some disagreement as to the mechanics involved. Fisher [1] noted that pools of cold water were created behind some hurricanes during parts of their lives, and that this phenomenon is apparently produced by upwelling in the ocean where the top layers are thermally stratified. Jordan [5], working with ship temperature data obtained prior to and following several typhoons in the Pacific, concluded that vertical mixing is the primary factor in the cooling of the surface layers and that mechanical stirring is probably more important than organized upwelling in this cooling process. He reached these conclusions mainly because the cooling was much more pronounced on the right side of the storm, (relative to the forward motion) the region of most intense wind and wave action.

Stevenson and Armstrong [9], by measuring sea temperatures in a zone of low-salinity shallow water near the coast in the northwestern Gulf of Mexico after the passage of hurricane Carla (1961), observed that bathythermograph traces revealed temperature inversions as great as 2.5° C. extending as deep as 83 m. They hypothesized that these inversions were formed in the surface waters through a lowering of the water temperature by a loss of heat to the hurricane. Leipper [7] made the most complete study to date in his detailed oceanographic investigation of that portion of the western Gulf through which hurricane Hilda (1964) passed. His observations indicated that the hurricane caused surface waters to be transported away from its center, cooling and mixing them to a slight degree as they moved. Convergence outside the storm area resulted in downwelling to 80 to 100 m. in that area, while water on the order of 5° C. colder upwelled from about 60 m. in the central region of the storm.

Hidaka and Akiba [3] developed a theory to explain cold water areas observed after hurricane passages which indicates a considerable amount of upwelling in the center of the storm. Ichiye [4], basing his results on fairly rigorous mathematical treatment, shows weak descending motion ahead of the storm, reaching somewhat larger though negligible values near the center, followed by strong vertical ascending motion thereafter. Gutman [2] and O'Brien [8] have also done some modeling of these phenomena. Gutman's solutions, which are obtained using variable stress as a function of time and then computing upwelling using continuity considerations, show maximum upwelling to occur at the center of the storm. O'Brien, on the other hand, derived a non-linear, theoretical model which describes upwelling and mixing induced in a stratified, rotating two-layer ocean by momentum transfer from a stationary, axially symmetric hurricane, and concluded that maximum upwelling occurs in the region of maximum turbulent shearing stress. O'Brien, however, worked with a stationary model while Gutman incorporated forward movement of the system in his model.

Thus, some question remains as to the origin of these cold spots observed in the wakes of hurricanes. Leipper's conclusion that upwelling is responsible is certainly reasonable based on the results of his cruise following the passage of hurricane Hilda (1964), but his inference that this upwelling occurred in the central region of the storm is still not completely proven. The "after Hilda" data were collected on a seven-day cruise, which means that the information obtained was not synoptic. Uncertainties of interpretation may have resulted from the fact that no consideration was given to the effects of the Gulf circulation on the thermal structure in the interval between the passage of the hurricane and the time the observations were made.

2. OBJECTIVES

During the past 12 yr. there have been only 11 hurricanes that have qualified as "great hurricanes", i.e., hurricanes with central pressure less than 950 mb. (Kraft [6]). Hurricane Betsy (1965) was one of these. It had qualified for this category before entering the Gulf of Mexico on September 8 and continued as an intense storm until shortly after landfall on September 10. Its maximum surface wind speed averaged about 120 kt. during the Gulf transect, and the eye diameter varied between 25 and 80 n. mi. during this period (see fig. 1).

Because of the size and intensity it was immediately recognized that this storm should have a profound effect on the thermal structure of the surface of the ocean. On September 9, the Director of the National Hurricane Research Laboratory, ESSA, agreed to support the Sea Air Interaction Laboratory's efforts to study these effects by making available a research aircraft from ESSA's Research Flight Facility for two flights to obtain sea-surface temperature data with an infrared radiometer in the wake of the storm. These missions were successfully completed on September 10 and 15.

The objective of this paper is to present the essentially real-time sea-surface temperature patterns obtained from these two flights, to discuss the similarities and differences between these results and those of previous investigators, and to suggest an investigation that could possibly lead to a more thorough understanding of the effects of the storm on the ocean thermal structure.

3. DATA COLLECTION

ESSA's Research Flight Facility is adequately equipped with multi-engine aircraft (two DC–6's, a DC–4, and a B–57) suitable for long-range reconnaissance and especially for hurricane research. The aircraft are outfitted with a system of meteorological sensors, radars, and photographic equipment as well as digital tape, analog, and photo-recording devices. For obtaining sea-surface temperatures from the DC–6 aircraft a Barnes IT–2 radiometer is employed, and the infrared (IR) data are recorded on an oscillographic recorder. This sensor is shock mounted vertically on a frame which fits inside the dropsonde chute during normal operation but which can easily be removed at any time during flight in order that in-flight calibration checks of the radiometer can be made. Two-point calibration checks are made approximately every 30 min. during flight using two agitated water baths of different temperatures. This rather frequent calibration helps to minimize readout errors resulting from changes in detector bias voltages, detector responsivity, amplifier gain, and amplifier drift of the radiometer. Such changes otherwise could lead to errors in the analysis of the data, which from experience could be as much as 1.5° to 2° C.

The track of the first flight, superimposed over the path of Betsy, is shown in figure 1. The times of three turning points are given for comparison with the hurricane time coordinates. The dashed lines denote the eye width as

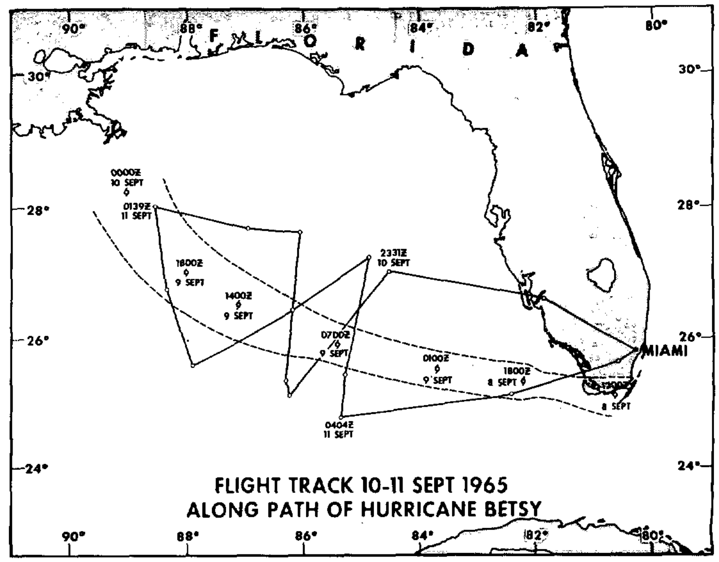

FIGURE 1.—Flight track of September 10–11, 1965, superimposed on the path of hurricane Betsy. Dashed lines define width of eye as determined by radar and reconnaissance aircraft.

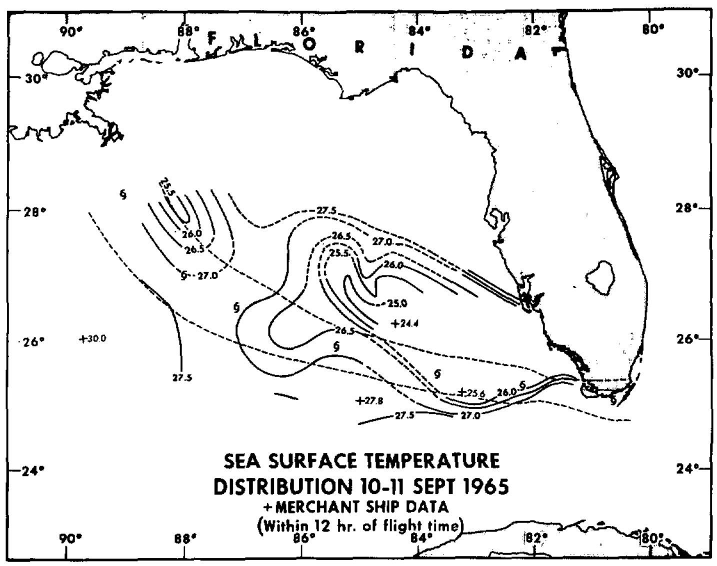

FIGURE 2.—Sea-surface temperature distribution on September 10–11, 1965.

determined by radars at Key West and New Orleans and by reconnaissance aircraft. Greater emphasis was placed on the right side of the storm track, although the left portion was adequately covered for detection of any colder water zones in that region.

A DC–6 research aircraft departed Miami on September 10 at 2225 GMT and returned after completing the mission at 0600 GMT on September 11. A flight altitude of between 800 and 1000 ft. was maintained throughout the flight. In addition to the IR data, meteorological information was also obtained throughout the flight at a sampling frequency of once every 10 sec. This information included: temperature, pressure, humidity, pressure altitude, radar altitude, and wind direction and wind speed as determined by the Doppler navigational system. Precise positioning was provided by means of Loran. The second flight on September 15, with the exception of the flight track, was conducted in the same manner as the first flight.

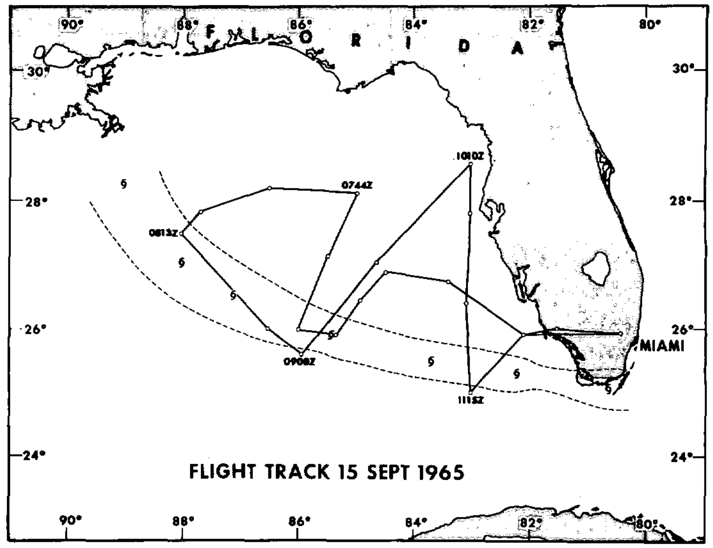

FIGURE 3.—Flight track of September 15, 1965, superimposed on the path of hurricane Betsy.

4. RESULTS

The sea-surface temperature distribution as measured on September 10–11 is shown in figure 2. The solid lines are isotherms drawn with a reasonable degree of certainty while the dashed lines, exclusive of the eye size indication, are extrapolated isotherms. The four temperatures at positions denoted by plus signs were obtained by merchant ships within 12 hr. of the time in which the IR data were collected. They were not used in analyzing the data and positioning the isotherms and are presented only for comparison with the airborne IR measurements for this flight.

At a glance the cold water zone induced by the hurricane is immediately the outstanding feature of this figure. It may be noted, however, that all of this cold water appears to the right of Betsy's path and farther from the center than the eye wall. Another interesting feature is the existence of two cores of cold water rather than one continuous trough. The northward curl of isotherms in the eastern core is of importance as will be shown below. The lowest temperature detected by the radiometer was slightly less than 25° C. This indication was recorded several miles north of the intersection of the leg of the flight occurring after the 2331 GMT turning point with the leg made prior to the 0404 GMT turning point on both tracks. The temperatures recorded on both tracks at each of the two intersections were in agreement with each other, thus indicating relative validity of all of the IR flight data.

Based on preliminary results of the first flight, a second plan was drawn up to cover some of the major features which had been observed. Major emphasis was placed on the north (right) side of the hurricane's path. At 0500 GMT on September 15, a DC–6 research aircraft departed Miami on another mission to collect sea-surface temperature data. Figure 3 shows the track of that flight. The aircraft returned to Miami at 1200 GMT after completing the second of the two nighttime flights made during the operation.

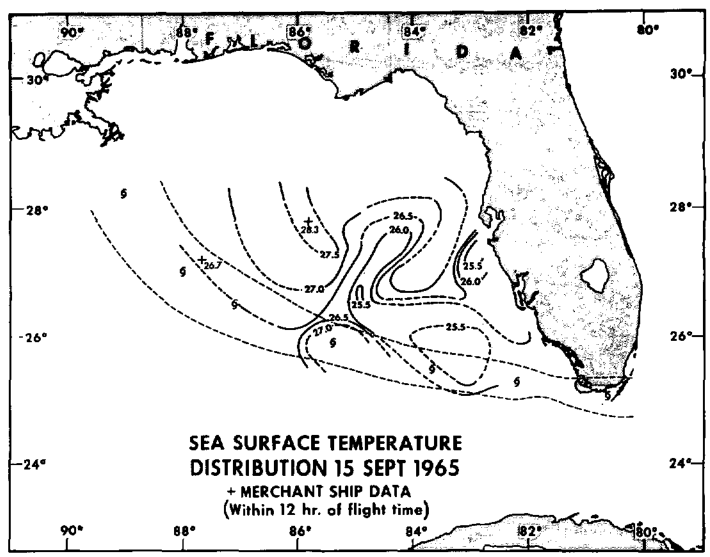

FIGURE 4.—Sea-surface temperature distribution on September 15, 1965.

The major feature of the second flight shown in figure 4 is an elongation to the northeast of the cold core detected on the earlier flight as indicated by the northward curl of the isotherms shown in figure 2. The data also indicate that during the five-day interval between flights the cold-core surface temperatures increased about 0.5° to 1.0° C.

Another interesting feature is the relatively small cold water area southwest of St. Petersburg and Tampa Bay. The shape of the isotherms indicates that this temperature structure is possibly associated with the bay circulation and may result from relatively cool rainwater runoff.

On the latter flight the aircraft did not traverse the area of the Gulf where the second cold core was detected on the western legs of the first flight.

5. CONCLUSIONS

The results of this experiment lead to two conclusions. First, they confirm the observations of the other investigators, as was expected, that hurricanes do cause well defined areas of cold water to occur at the sea surface in their wakes. The surface temperature data alone, however, do not establish whether maximum upwelling occurs in the central region of the storm, as concluded by Gutman [2] and Leipper [7], or whether it occurs in the region of maximum turbulent shearing stress as concluded by O'Brien [8]. Certainly the positions of the cold water areas observed on these flights fit more closely positions of cold water zones described for Pacific typhoons by Jordan [5], but again it is not obvious from the IR data that vertical mixing induced by mechanical stirring is more important than organized upwelling in this cooling process as he concluded.

Perhaps even more important than the first observation above, at least from a data collection standpoint, is the rapid deformation of the eastern cold water core observed in the interval between the two flights. This temperature pattern change could have been realized by a northeastward flowing current of less than 1 kt. Such a current, the Yucatan Current, is a feature of the surface circulation of the Gulf of Mexico.

The emphasis here is on the sampling time involved in acquiring data for the solution of this particular problem. On the one hand a research ship can obtain, in addition to surface temperatures, sub-surface data which are essential to answering the questions concerning upwelling and mixing. A voyage to obtain this information, however, requires a considerable amount of time—about 10 days to cover such an area as discussed here.

The aircraft, on the other hand, covered the area in less than 10 hr., but it was not suitably equipped to obtain sub-surface temperatures. It would be desirable, then, to combine the speed of the aircraft with the versatility demonstrated by the ship for successfully attacking the problem. Wilkerson [10] points out that with an airborne infrared sensor and an air-droppable expendable bathythermograph, observations can now be made of sea-surface temperatures and temperatures with depth, thus providing a near-synoptic picture of the thermal structure of the first few hundred meters of the ocean over a large area. It would take several ships at considerably greater expense to duplicate such observations. The Sea-Air Interaction Laboratory plans in the near future to employ these techniques of airborne oceanography in a more detailed synoptic study of the effects of a hurricane on the thermal structure of the ocean by measuring surface and sub-surface temperatures both ahead of and behind the storm.

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REFERENCES

1. E. L. Fisher, "Hurricanes and Sea-Surface Temperature Field," *Journal of Meteorology*, vol. 15, No. 3, June 1958, pp. 328–333.
2. G. Gutman, "A Preliminary Study of Ocean Conditions as Affected by a Hurricane Passage," Paper presented at the Fourth Technical Conference on Hurricanes and Tropical Meteorology, Miami Beach, Fla., Nov. 22–24, 1965.
3. K. Hidaka and Y. Akiba, "Upwelling Induced by a Circular Wind System," *Records of Oceanographic Works in Japan*, vol. 2, No. 1, Mar. 1955, pp. 7–18.
4. T. Ichiye, "On the Variation of Oceanic Circulation, Part 5," *Geophysical Magazine*, Tokyo, vol. 26, No. 4, Aug. 1955, pp. 283–299.
5. C. L. Jordan, "On the Influence of Tropical Cyclones on the Sea Surface Temperature Field," *Proceedings, Symposium on Tropical Meteorology*, J. W. Hutchins (ed.), New Zealand Meteorology Service, Wellington, 1964, pp. 614–622.
6. R. H. Kraft, "Great Hurricanes, 1955–1965," *Mariners Weather Log*, vol. 10, No. 6, Nov. 1966, pp. 200–202.
7. D. F. Leipper, "Observed Ocean Conditions and Hurricane Hilda, 1964," *Journal of the Atmospheric Sciences*, 1967 (in press).
8. J. J. O'Brien, "The Non-Linear Response of a Two-Layer, Baroclinic Ocean to a Stationary, Axially-Symmetric Hurricane," Texas A&M University, Department of Oceanography, Reference 65-34T, Dec. 1965, 98 pp.
9. R. E. Stevenson and R. S. Armstrong, "Heat Loss From the Waters of the Northwest Gulf of Mexico During Hurricane Carla," *Geofisica Internacional*, vol. 5, No. 2, 1965, pp. 49–57.
10. J. W. Wilkerson, "Airborne Oceanography," *Geo-Marine Technology*, vol. 2, No. 8, Sept. 1966, pp. 9–16.

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